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The Evolutionary History of Local Group Irregular Galaxies

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Abstract

Irregular (Irr) and dwarf irregular (dIrr) galaxies are gas-rich galaxies with recent or ongoing star formation. In the absence of spiral density waves, star formation occurs largely stochastically. The scattered star-forming regions tend to be long-lived and migrate slowly. Older populations have a spatially more extended and regular distribution. In fast-rotating Irrs high star formation rates with stronger concentration toward the galaxies' center are observed, and cluster formation is facilitated. In slowly or nonrotating dIrrs star formation regions are more widely distributed, star formation occurs more quiescently, and the formation of OB associations is common. On average, Irrs and dIrrs are experiencing continuous star formation with amplitude variations and can continue to form stars for another Hubble time.

Irrs and dIrrs exhibit lower effective yields than spirals, and [α/Fe] ratios below the solar value. This may be indicative of fewer Type II supernovae and lower astration rates in their past (supported by their low present-day star formation rates). Alternatively, many metals may be lost from the shallow potential wells of these galaxies due to selective winds. The differences in the metallicity-luminosity relation between dIrrs and dwarf spheroidals (which, despite their lower masses, tend to have too high a metallicity for their luminosity as compared to dIrrs) lends further support to the idea of slow astration and slow enrichment in dIrrs. The current data on age-metallicity relations are still too sparse to distinguish between infall, leaky-box, and closed-box models. The preferred location of dIrrs in the outer parts of galaxy groups and clusters and in the field as well as the positive correlation between gas content and distance from massive galaxies indicate that most of the dIrrs observed today probably have not yet experienced significant interactions or galaxy harassment.

1.1 Introduction

In this contribution, I will focus on the evolutionary histories of irregular (Irr) and dwarf irregular (dIrr) galaxies, including their chemical evolution. The name "irregular" refers to the irregular, amorphous appearance of these galaxies at optical wavelengths, where the light contribution tends to be dominated by scattered bright H II regions and their young, massive stars. Irrs are typically gas-rich galaxies that lack spiral density waves as well as a discernible bulge or nucleus. Many Irrs are disk galaxies and appear to be an extension of late-type spirals. The most massive disky Irrs with residual spiral structure are also called

Magellanic spirals; e.g., the Large Magellanic Cloud (LMC) (Kim et al. 1998) is a barred Magellanic spiral. Looser and more amorphous Irrs like the Small Magellanic Cloud (SMC) are sometimes also referred to as Magellanic irregulars (or barred Magellanic irregulars if a bar is present); see de Vaucouleurs (1957). A different system of subdivisions was suggested by van den Bergh in his DDO luminosity classification system (van den Bergh 1960, 1966). DIrrs are simply less massive, less luminous Irrs; the distinction between the two is a matter of definition rather than physics. Typical characteristics of dIrrs are a central surface brightness $\mu_V \lesssim 23$ mag arcsec^{-2}, a total mass of $M_{\rm tot} \lesssim 10^{10} M_\odot$, and an H I mass of $M_{\rm HI} \lesssim 10^9 M_\odot$. Solid body rotation is common among the Irrs and more massive dIrrs, while low-mass dIrrs do not show measurable rotation; here random motions dominate. A typical characteristic of Irrs and dIrrs alike is ongoing or recent star formation. The star formation intensity may range from burst-like, strongly enhanced activity, to slow quiescent episodes. Irrs and dIrrs can continue to form stars over a Hubble time (Hunter 1997).

Substantial progress has been made in the photometric exploration of the star formation histories of Irrs and dIrrs over the past decade, largely thanks to the superior resolution of the *Hubble Space Telescope*. There is still very little known about the progress of the chemical evolution in these galaxies as a function of time, but the advent of 6-m to 10-m class telescopes and their powerful spectrographs is beginning to change this situation. The most detailed information is available for nearby Irr and dIrr galaxies in the Local Group, most notably the LMC, which is the Irr galaxy closest to the Milky Way.

1.2 Distribution and Census of Irregulars in the Local Group

The Local Group, our immediate cosmic neighborhood, resembles other nearby galaxy groups in many ways, including in its galaxy content, structure, mass, and other properties (e.g., Karachentsev et al. 2002a, b). It is our best local laboratory to study galaxy evolution at the highest possible resolution and in the greatest possible detail. The Local Group contains two dominant spiral galaxies surrounded by a large number of smaller galaxies. Thirty-six galaxies are currently believed to be members of the Local Group if a zero-velocity surface of 1.2 Mpc is adopted (Courteau & van den Bergh 1999; Grebel, Gallagher, & Harbeck 2003)*. The smaller galaxies in the Local Group include a spiral galaxy (M33), 11 gas-rich Irr and dIrr galaxies (including low-mass, so-called transition-type galaxies that comprise properties of both dIrrs and dwarf spheroidals), four elliptical and dwarf elliptical galaxies, and 17 gas-deficient dwarf spheroidal (dSph) galaxies. For a listing of the basic properties of these galaxies, see Grebel et al. (2003). Their three-dimensional distribution is illustrated in Grebel (1999; Fig. 3). Recent reviews of Local Group galaxies include Grebel (1997, 1999, 2000), Mateo (1998), and van den Bergh (1999, 2000).

DIrrs are the second most numerous galaxy type in the Local Group. While new dwarf members of the Local Group are still being discovered (e.g., Whiting, Hau, & Irwin 1999), these tend to be gas-deficient, low-mass dSph galaxies, which have intrinsically low optical surface brightnesses and cannot be found from their H I 21 cm emission lines. The Irr and dIrr census of the Local Group appears to be complete.

Irrs and dIrrs are found in galaxy groups and clusters as well as in the field and exhibit little concentration toward massive galaxies in contrast to early-type dwarfs. This morphological segregation is clearly seen in the Local Group and in nearby groups (Fig. 1.1). It

* Note that recent kinematic estimates suggest an even smaller radius of (0.94 ± 0.10) Mpc for the zero-velocity surface (Karachentsev et al. 2002c), which reduces the above number of Local Group dwarf galaxies by two.

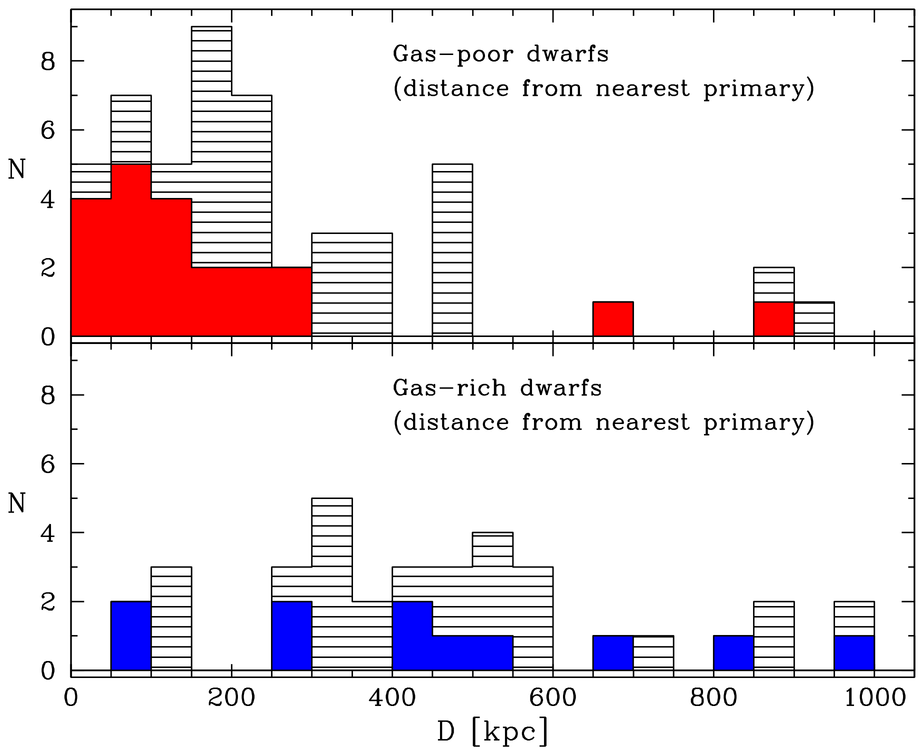

Fig. 1.1. Morphological segregation in the Local Group (filled histograms; see Grebel 2000) and in the M81 and Cen A groups (dashed histograms; input data from Karachentsev et al. 2002a, b). Note the pronounced concentration of gas-poor, early-type dwarfs around the nearest massive primary galaxy, while the gas-rich, late-type dwarfs show less concentration and are more widely distributed. This may be a signature of the impact of environmental effects, such as gas stripping.

becomes even more pronounced in galaxy clusters, where the distribution of Irrs shows the least concentration of all galaxy types toward the cluster core (e.g., Conselice, Gallagher, & Wyse 2001, and references therein), which has been attributed to continuing infall of Irrs and subsequent harassment. Conversely, in very loose groups or "clouds" (such as the Canes Venatici I Cloud) that are still far from approaching dynamical equilibrium, an overabundance of Irrs and dIrrs is observed as compared to early-type dwarfs (Karachentsev et al. 2003a), indicative of a lack of interactions.

1.3 The Interstellar Medium of Local Group Irregulars

1.3.1 The Magellanic Clouds

The Magellanic Clouds are the two most massive Irrs in the Local Group, and the only two Irrs in immediate proximity to a massive spiral galaxy. Their distances from the Milky Way are 50 kpc (LMC) and 60 kpc (SMC), respectively. They are the only two Local

Group Irrs that are closely interacting with each other (and with the Milky Way). According to the earlier definition, the SMC qualifies as a dIrr.

The global distribution of neutral hydrogen within the Magellanic Clouds and other comparatively massive Irrs tends to show a regular, symmetric appearance, in contrast to their visual morphology. On smaller scales, the H I is flocculent and exhibits a complicated fractal pattern full of shells and clumps (e.g., Kim et al. 1998; Stanimirovic et al. 1999). The lack of correlation between the H I shells and the optically dominant H II shells suggests that H I shells live longer than the OB stars that caused them initially (Kim et al. 1999). The H I associated with H II regions is usually more extended than the ionized regions. The fractal structure of the neutral gas is self-similar on scales from tens to hundreds of pc (Elmegreen, Kim, & Staveley-Smith 2001) and appears to result from the turbulent energy input caused by winds of recently formed massive stars and supernova explosions.

With 0.5×10^9 $M_\odot$ (Kim et al. 1998) the LMC's gaseous component contributes about 9% to its total mass, while it is $\sim$ 21% in the SMC (H I mass of 4.2×10^8 $M_\odot$; Stanimirovic et al. 1999). In comparison to the Milky Way, the gas-to-dust ratio is roughly 4 times lower in the LMC (Koornneef 1982) and about 30 times lower in the SMC (Stanimirovic et al. 2000), implying a smaller grain surface area per hydrogen atom, fewer coolants, and thus a reduced H_2 formation efficiency (Dickey et al. 2000; Stanimirovic et al. 2000; Tumlinson et al. 2002). Indeed, the total diffuse H_2 mass is only 8×10^6 $M_\odot$ in the LMC and 2×10^6 $M_\odot$ in the SMC, which corresponds to 2% and 0.5% of their H I masses, respectively (Tumlinson et al. 2002). Also the reduced CO emission from both Clouds (3–5 times lower than expected for Galactic giant molecular clouds) is indicative of the high UV radiation field in low-metallicity environments and hence high CO photodissociation rates (Israel et al. 1986; Rubio, Lequeux, & Boulanger 1993). While high dust content is correlated with high H_2 concentrations, H_2 does not necessarily trace CO or dust (Tumlinson et al. 2002).

Photoionization through massive stars is the main contributor to the optical appearance of the interstellar medium (ISM) at $\sim 10^4$ K in the Clouds and other gas-rich, star-forming galaxies. The LMC has a total Hα luminosity of 2.7×10^{40} erg s^{-1}; 30% to 40% is contributed by diffuse, extended gas (Kennicutt et al. 1995). In the LMC nine H II supershells with diameters > 600 pc are known (Meaburn 1980). Their rims are marked by strings of H II regions and young clusters/OB associations. The standard picture for supershells suggests that these are expanding shells driven by propagating star formation (e.g., McCray & Kafatos 1987). However, an age *gradient* consistent with this scenario was not detected in the largest of these supershells, LMC4 (Dolphin & Hunter 1998). Nor are other LMC supershells expanding as a whole, but instead appear to consist of hot gas confined between H I sheets and show localized expansion. Supershells in several other galaxies neither show evidence for expansion (e.g., Points et al. 1999), nor the expected young massive stellar populations (Rhode et al. 1999). In contrast, the three H I supershells and 495 giant shells in the SMC appear to be expanding (Staveley-Smith et al. 1997; Stanimirovic et al. 1999).

The hot, highly ionized corona of the LMC with collisionally ionized gas (temperatures $\gtrsim 10^5$ K) (Wakker et al. 1998) is spatially uncorrelated with star-forming regions. A hot halo is also observed around the SMC, but here clear correlations with star-forming regions are seen. This corona may be caused in part by gas falling back from a galactic (i.e., SMC) fountain (Hoopes et al. 2002). The O VI column density exceeds the corresponding Galactic value by 1.4 (Hoopes et al. 2002), consistent with the longer cooling times expected at lower metallicities (Edgar & Chevalier 1986).

The Magellanic Clouds, which only have a deprojected distance of 20 kpc from each other, interact with each other and with the Milky Way. Apart from an impact on the structure and star formation histories of these three galaxies (e.g., Hatzidimitriou, Cannon, & Hawkins 1993; Kunkel, Demers, & Irwin 2000; Weinberg 2000; van der Marel et al. 2002), this has given rise to extended gaseous features surrounding the Magellanic Clouds (Putman et al. 2003, and references therein). Part of these are likely caused by tidal interactions, but ram pressure appears to have played an important role as well (Putman et al. 1998; Mastropietro et al. 2004). Metallicity determinations for gas in the Magellanic Stream, which is trailing behind the Magellanic Clouds and subtends at least $10^\circ \times 100^\circ$ on the sky, confirm that the gas is not primordial (Lu et al. 1998; Gibson et al. 2000). The H_2 detected in the leading arm of the Stream may originally have formed in the SMC (Sembach et al. 2001). No stars are known to be connected with the Magellanic Stream (Putman et al. 2003).

Another prominent H I feature is the "Magellanic Bridge" or InterCloud region ($10^8\ M_\odot$; Putman et al. 1998), which connects the LMC and SMC. Cold (20 to 40 K) H I gas has been detected in the Bridge (Kobulnicky & Dickey 1999), and recent star formation occurred there over the past 10 to 25 Myr (Demers & Battinelli 1998). Intermediate-age stars are also present in parts of the Bridge (carbon stars: Kunkel et al. 2000, and references therein). Higher ionized species with temperatures up to $\sim 10^5$ K show an abundance pattern suggesting depletion into dust (Lehner et al. 2000). Interestingly, the metallicities of young stars in the Bridge were found to be [Fe/H] ≈ -1.1 dex (Rolleston et al. 1999), 0.4 dex below the mean abundance of the young SMC population, which is inconsistent with the proposed tidal origin 200 Myr ago (Murai & Fujimoto 1980; Gardiner & Noguchi 1996).

1.3.2 More Distant Dwarf Irregular Galaxies

The other Local Group dIrrs are more distant from the dominant spirals, and fairly isolated. Interactions may still occur, but if this happens the interaction partners tend to be gas clouds rather than galaxies. Generally, star formation activity and gas content decrease with galaxy mass, but the detailed star formation histories and ISM properties of the dIrrs present a less homogeneous picture.

NGC 6822, a dIrr at a distance of ~ 500 kpc, is embedded in an elongated H I cloud with numerous shells and holes. Its total H I mass is $1.1 \times 10^8\ M_\odot$, ~ 7% of its total mass. The masses of individual CO clouds reach up to $(1-2) \times 10^5\ M_\odot$ (Petitpas & Wilson 1998), while the estimated H_2 content is 15% of the H I mass (Israel 1997), and the dust-to-gas mass ratio is $\sim 1.4 \times 10^{-4}$ (Israel, Bontekoe, & Kester 1996). NGC 6822 contains many H II regions. Its huge supershell (2.0×1.4 kpc) was likely caused by the passage of and interaction with a nearby $10^7\ M_\odot$ H I cloud and does not show signs of expansion (de Blok & Walter 2000). The older stars in IC 10 describe an elliptical, extended halo (Letarte et al. 2002) distinct from the elongated H I distribution. The latter, however, is traced closely by a population of young blue stars (~ 180 Myr) that appear to have formed following the interaction with the passing H I cloud (de Blok & Walter 2003; Komiyama et al. 2003) some 300 Myr ago. In NGC 6822, the H I distribution is thus only slightly more extended than the stellar loci.

The H I of IC 10 (distance 660 kpc) is 7.2 times more extended than its Holmberg radius (Tomita, Ohta, & Saitō 1993). While the inner part of the neutral hydrogen of IC 10 is a regularly rotating disk full of shells and holes, the outer H I gas is counter-rotating (Wilcots & Miller 1998). IC 10 is currently experiencing a massive starburst, which is possibly trig-

gered and fueled by an infalling H I cloud (Saitō et al. 1992; Wilcots & Miller 1998). IC 10 contains a nonthermal superbubble that may be the result of several supernova explosions (Yang & Skillman 1993). The masses of the CO clouds in IC 10 appear to be as high as up to $5 \times 10^6\ M_\odot$ (Petitpas & Wilson 1998), which would indicate that more than 20% of this galaxy's gas mass is molecular. Owing to the high radiation field and the destruction of small dust grains, the ratio of far-infrared [C II] to CO 1–0 emission is a factor 4 larger than in the Milky Way (Bolatto et al. 2000), resulting in small CO cores surrounded by large [C II]-emitting envelopes (Madden et al. 1997). Two H_2O masers were detected in dense clouds in IC 10, marking sites of massive star formation (Becker et al. 1993). The internal dust content of IC 10 is high, and its properties prompted Richer et al. (2001) to suggest that this galaxy should actually be classified as a blue compact dwarf.

Less detailed information is available for the ISM in the other Local Group dIrrs, which do not appear to be involved in ongoing interactions and which are evolving fairly quiescently. The H I in these dIrrs may be up to 3 times more extended than the optical galaxy and is clumpy on scales of 100 to 300 pc. The most massive clumps reach $\sim 10^6\ M_\odot$. H I concentrations tend to be close to H II regions. Some dIrrs contain cold H I clouds associated with molecular gas. The total H I masses are usually $< 10^9\ M_\odot$, and less than $10^7\ M_\odot$ for transition-type dwarfs. The center of the H I distribution coincides roughly with the optical center of the dIrrs, although the H I may show a central depression surrounded by an H I ring or arc (e.g., SagDIG, Leo A), possibly a consequence of star formation, or the H I may be off-centered (e.g., Phoenix; St-Germain et al. 1999). In low-mass dIrrs there are no signatures of rotation, but these may be obscured by expanding shells and bubbles. Further details are given in Lo, Sargent, & Young (1993), Young & Lo (1996, 1997), Elmegreen & Hunter (2000), and Young et al. (2003).

Lower gravitational pull and the lack of shear in the absence of differential rotation imply that H I shells may become larger and are long-lived (Hunter 1997). Diameters, ages, and expansion velocities of the H I shells increase with later Hubble type (Walter & Brinks 1999) and scale approximately with the square root of the galaxy luminosity (Elmegreen et al. 1996). Shell-like structures, H I holes, or off-centered gas may be driven by supernovae and winds from massive stars following recent star formation episodes or tidal interactions.

For a review on nebular abundances in Irrs, see the contribution by Garnett (2004). Here it should only be mentioned that the effective yields in Irrs computed from gas-phase abundances are lower than those in the main stellar disks of spirals. Lower effective yields are also correlated with lower rotational velocities (Garnett 2002). This is interpreted as preferential metal loss through winds in the more shallow potential wells of Irrs and dIrrs, but may also be due to lower astration levels (e.g., Pilyugin & Ferrini 2000). For a review of the general ISM properties in Local Group dwarf galaxies, see Grebel (2002a).

1.4 Large-scale Star Formation and Spatial Variations

The dwarf galaxies in the Local Group vary widely in their star formation and enrichment histories, times and duration of their major star formation episodes, and fractional distribution of ages and subpopulations. Indeed, when studied in detail, no two dwarf galaxies turn out to be alike, not even if they are of the same morphological type or have similar luminosities (Grebel 1997). On the other hand, in spite of their individual differences, they do follow certain common global correlations such as increasing mean metallicity with luminosity (§1.6.2).

1.4.1 Large-scale Star Formation

The ISM properties of Irrs and dIrrs outlined in the previous section already show that there are spatial variations in star formation history and other characteristics within these galaxies. In general, dwarf galaxies of all types show a tendency for the younger populations to be more centrally concentrated (and possibly more chemically enriched), whereas older populations are more extended (Grebel 1999, 2000; Harbeck et al. 2001). In Irr and dIrr galaxies, H II regions tend to be located within the part of the galaxy that shows solid body rotation and are usually even more centrally concentrated (Roye & Hunter 2000). Star-forming regions may, however, be found out to six optical scale lengths, indicating that star formation is truncated at lower gas density thresholds than in spirals (Parodi & Binggeli 2003). In dIrrs dominated by chaotic motions, the degree of central concentration of recent star formation is lower, whereas fast-rotating Irrs tend to exhibit the highest central concentrations. The same trend also holds for the star formation activity: low-mass dIrrs with no measurable rotation also have lower star formation rates (Roye & Hunter 2000; Parodi & Binggeli 2003).

How does star formation progress in irregular galaxies? Irrs and the more massive dIrrs usually contain multiple distinct regions of concurrent star formation. These regions often remain active for several 100 Myr, are found throughout the main body of these galaxies (see above), and can migrate. This is illustrated in Figure 1.2 for the LMC, where the large-scale star formation history of the last $\sim$ 250 Myr (approximately one rotation period) is shown (see Grebel & Brandner 1998 for full details). Note how some of the active regions have continued to form stars over extended periods and propagated slowly, whereas others only became active during the past 30 Myr. The star formation complexes resemble superassociations and may span areas of a few hundred pc (Grebel & Brandner 1998). In supershells, typical time scales for continuing star formation on length scales of 0.5 kpc range from 15 to 30 Myr, usually without showing clear signs of spatially directed propagation with time (see also Grebel & Chu 2000 and §1.3.1). CO shows a strong correlation with H II regions and young ($<$ 10 Myr) clusters, but only little with older clusters and supernova remnants (Fukui et al. 1999; cf. Banas et al. 1997). Massive CO clouds have typical lifetimes of $\sim$ 6 Myr and are dissipated within $\sim$3 Myr after the formation of young clusters (Fukui et al. 1999; Yamaguchi et al. 2001). Spatially resolved star formation histories have also been derived for two dIrr galaxies just beyond the Local Group covering the past 500–700 Myr. They reveal similar long-lived, gradually migrating zones of star formation (Sextans A: Van Dyk, Puche, & Wong 1998; Dohm-Palmer et al. 2002; GR 8: Dohm-Palmer et al. 1998), as seen in the more massive Magellanic Clouds.

In low-mass dIrrs one usually observes only one single low-intensity star-forming region. DIrrs and transition-type dIrr/dSph galaxies tend to be fairly quiescent, often having experienced the bulk of their star formation at earlier times. (In fact, transition-type dwarfs resemble dSphs in their gradually declining star formation rates; see Grebel et al. 2003 for details.) Evidence for migrating star formation is found in low-mass dIrrs as well, albeit on smaller scales owing to the smaller sizes of these galaxies (e.g., Phoenix: Martínez-Delgado, Gallart, & Aparicio 1999).

1.4.2 Intermediate-age and Old Stellar Populations

Irrs and massive dIrrs tend to show extended halos of intermediate-age stars (ages $\sim$ 1 to $\sim$ 10 Gyr), which can be conveniently traced by carbon stars (e.g., Letarte et al. 2002).

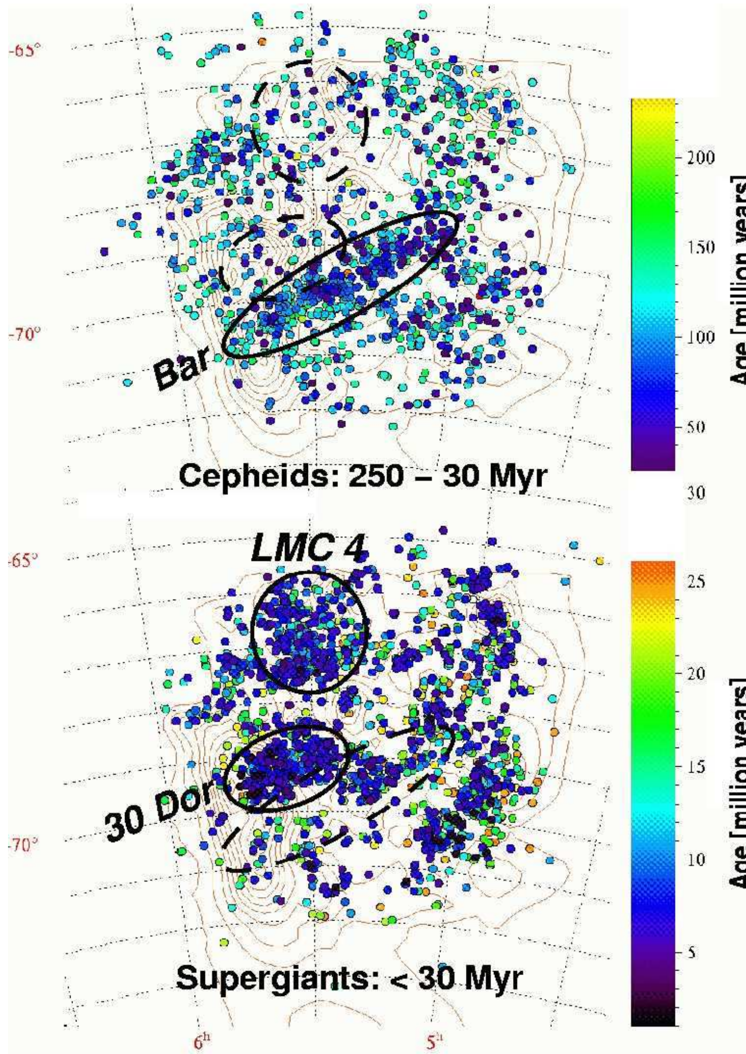

Fig. 1.2. Large-scale star formation patterns in the Large Magellanic Cloud spanning the past ~ 250 Myr. The individual dots correspond to age-dated Cepheids (*upper panel*) and supergiants (*lower panel*). A few prominent features like the LMC bar, supershell LMC 4, and 30 Doradus are marked by solid and dashed lines. Note how star formation migrated along the LMC's bar and finally vanished in its southernmost past, and how other regions such as 30 Doradus and LMC 4 only became strongly active over the past ~ 30 Myr. Within the time scales depicted here, which incidentally correspond to roughly one rotation period, stars are not expected to have migrated far from their birthplaces. (From Grebel & Brandner 1998.)

In the Magellanic Clouds, the density distributions of different populations ages become increasingly more regular and extended with increasing age (e.g., Cioni et al. 2000; Zaritsky et al. 2000), whereas the young populations are responsible for the irregular appearance of

these two galaxies. The centroids of the different populations do not always coincide. Features resembling stellar bars are found in many dIrrs, which do not necessarily coincide with the peak H I distribution or its centroid. In low-mass dIrrs there are not enough intermediate-age tracers such as C stars to say much about the distribution of these populations (see, e.g., Battinelli & Demers 2000); the number of C stars decreases with absolute galaxy luminosity and also with galaxy metallicity (see Groenewegen 2002 for a recent review and census of C stars in the Local Group).

All Irr and dIrr galaxies examined in detail so far show clear evidence for the presence of old ($>$ 10 Gyr) populations, a property that they appear to share with all galaxies whose stellar population have been resolved. For instance, deep ground-based imaging of the "halos" of dIrrs led to the detection of old red giant branches (e.g., Minniti & Zijlstra 1996; Minniti, Zijlstra, & Alonso 1999). In closer dIrrs, horizontal branch stars have been detected in field populations (e.g., IC 1613: Cole et al. 1999; Phoenix: Holtzman, Smith, & Grillmair 2000; WLM: Rejkuba et al. 2000; Leo A: Dolphin et al. 2002) and in globular clusters (e.g., WLM: Hodge et al. 1999). Horizontal branch stars are unambiguous tracers of ancient populations. In the closest dIrrs and Irrs even the old main sequence turn-offs have been resolved, allowing differential age dating. Interestingly (with the possible exception of the SMC), the oldest datable populations in all nearby dwarf galaxies turn out to be indistinguishable in age from each other and from the Milky Way, indicating a common epoch of early star formation (e.g., Olsen et al. 1998; Johnson et al. 1999; see Grebel 2000 for a full list of references). Apart from the recent interaction in NGC 6822 (§1.3.2), the old populations also are usually the most extended ones. However, their fractions vary: in some cases they only constitute a tiny portion of the stellar content of their parent galaxy.

1.4.3 Modes of Star Formation

The ISM in dIrrs is highly inhomogeneous and porous, full of small and large shells and holes. The global gas density tends to be significantly below the Toomre criterion for star formation (van Zee et al. 1997). Stochastic, star formation may be driven by homogeneous turbulence, which creates local densities above the star formation threshold (e.g., Stanimirovic et al. 1999). Self-propagating stochastic star formation (Gerola & Seiden 1978; Gerola, Seiden, & Schulman 1980; Feitzinger et al. 1981) can lead to structures of sizes of up to 1 kpc, in which star formation processes remain active for 30–50 Myr, or to the formation of long-lived spiral features if an off-centered bar is present (Gardiner, Turfus, & Putman 1998). In the absence of shear, star formation continues along regions of high H I column density, fueled by the winds of recently formed stars and supernovae explosions.

Dense gas concentrations may, however, also remain inactive for hundreds of Myr, and there are not usually obvious triggers for the onset of star formation (see Dohm-Palmer et al. 2002). This may be different in nonquiescently evolving, starbursting dIrrs like IC 10: gas accretion or other interactions may be triggering the starburst (see §1.3.2). The existence of isolated dIrrs with continuous star formation outside of groups shows that external triggers are not needed. Quiescently evolving dIrrs exhibit widely distributed star formation and have very small color gradients, whereas starbursting dIrrs show much more concentrated star formation and strong color gradients (van Zee 2001). The analysis of 72 dIrr galaxies in nearby groups and in the field revealed that the radial distribution of star-forming regions follows on average an annulus-integrated exponential distribution, and that secondary star-

Table 1.1. *Star Clusters in the Local Group Irr and dIrr Galaxies*

Galaxy	Type	D_{Sp} [kpc]	M_V [mag]	N_{GC}	S_N	[Fe/H] [dex]	N_{OC}
LMC	Ir III-IV	50	–18.5	$\sim$13	0.5	–2.3, –1.2	$\gtrsim$4000
SMC	Ir IV/IV-V	63	–17.1	1	0.1	–1.4	$\gtrsim$2000
NGC 6822	Ir IV-V	500	–16.0	1	0.4	–2.0	$\sim$20
WLM	Ir IV-V	840	–14.4	1	1.7	–1.5	$\geq$1
IC 10	Ir IV:	250:	–16.3	0	0	—	$\gtrsim$13
IC 1613	Ir V	500	–15.3	0	0	—	$\gtrsim$5
Phe	dIrr/dSph	405	–12.3	[4:]	[48:]	—	?
PegDIG	Ir V	410	–11.5	0	0	—	$\lesssim$3
LGS 3	dIrr/dSph	280	–10.5	0	0	—	$\lesssim$13

Notes: Only galaxies known to contain star clusters are listed. D_{Sp} denotes the distance to the nearest spiral galaxy (M31 or Milky Way, Col. 3). N_{GC} and N_{OC} (Cols. 5 & 8) list the number of globular clusters and open clusters, respectively. Note that the globular cluster suspects in Phoenix are highly uncertain. S_N (Col. 6) is the specific globular cluster frequency. When two values are listed in Col. 7 (metallicity), these indicate the most metal-rich and most metal-poor globular clusters. For more details, a full list of galaxies with star clusters in the Local Group, and references, see Grebel (2002b).

forming peaks at larger distances are consistent with internal triggering via stochastic, self-propagating star formation (Parodi & Binggeli 2003).

Quiescent dIrrs tend to form OB associations, while massive starbursts can lead to the formation of more compact star clusters. The number of massive clusters tends to correlate with galaxy mass (i.e., roughly with luminosity; see, e.g., Parodi & Binggeli 2003). For instance, in the dIrr NGC 6822 on average one cluster is formed per 6×10^6 years (a much smaller number than in the more massive LMC), while an OB association forms every 7×10^5 years, similar to the LMC (Hodge 1980). The distinctive, well-separated peaks in the formation rate of populous clusters in the LMC, however, seem to be caused by close encounters with the Milky Way and the SMC (Gardiner, Sawa, & Fujimoto 1994; Girardi et al. 1995; Lin, Jones, & Klemola 1995); it is surprising that no corresponding enhancement in the SMC's fairly continuous cluster formation rate is seen. Generally, old globular clusters are rare in dIrrs. For the cluster census in Local Group Irr and dIrr galaxies, see Table 1.1.

On a global, long-term scale, star formation in dIrrs has essentially occurred continuously at a constant rate with amplitude variations of 2–3 (Tosi et al. 1991; Greggio et al. 1993), is largely governed by internal, local processes, and will likely continue for another Hubble time (Hunter 1997; van Zee 2001).

1.5 Metallicity and Age

1.5.1 Young Populations and Chemical Homogeneity

The gas in Irrs and dIrrs is fairly well mixed, and mixing must proceed rapidly considering how homogeneous present-day H II region abundances at different locations within the same galaxy are. Nebular abundances of ionized gas trace the youngest populations and the chemical composition of the star-forming material. Why there is such a high degree of homogeneity is not fully understood, nor is it clear how the mixing proceeds; mechanisms

may include winds and turbulence. Inhomogeneities are only expected to be detectable very shortly after the responsible stellar population formed (e.g., when pollution by Wolf-Rayet stars occurs; see Kobulnicky et al. 1997). Note that such global chemical homogeneity appears to be less pronounced in gas-deficient dSph galaxies, which seem to have experienced different star formation and chemical enrichment histories than dIrrs (see, e.g., Harbeck et al. 2001; Grebel et al. 2003).

If Irrs and dIrrs are chemically homogeneous, one would expect to measure comparable abundances in H II regions and young stars of a given dIrr, since both trace the same population. Due to their proximity, in the Magellanic Clouds supergiants, giants, and even massive main sequence stars can be analyzed with high-dispersion spectroscopy and individual element ratios can be measured. Indeed, in the Magellanic Clouds good agreement is found between nebular and stellar abundances (e.g., Hill, Andrievsky, & Spite 1995; Andrievsky et al. 2001). Star-to-star variations in the overall metallicity of young stars (B to K supergiants and B main sequence stars) are small (± 0.1 dex: Hill 1997; Luck et al. 1998; Venn 1999; Rolleston, Trundle, & Dufton 2002), and there is no evidence for a significant Population I metallicity spread in either Cloud. Also, the differences between the stellar abundances in young clusters and field stars are small (Gonzalez & Wallerstein 1999; Hill 1999; Korn et al. 2000, 2002; Rolleston et al. 2002). The mean metallicity of the young population in the LMC is [Fe/H] ≈ -0.3 dex and ~ -0.7 dex in the SMC.

Very good agreement between young stellar and nebular abundances is also found in the more distant dIrrs NGC 6822 (B supergiants: Muschielok et al. 1999; A supergiants: Venn et al. 2001, both yielding [Fe/H] = –0.5 dex), GR 8, and Sex A (Venn et al. 2004). The two blue supergiants analyzed in WLM, on the other hand, have clearly higher metallicities than found in its H II regions (Venn et al. 2003). The reasons for this discrepancy in WLM are still unknown.

1.5.2 Intermediate-age/Old Populations and Chemical Inhomogeneity

Whereas young populations in dIrrs tend to be fairly homogeneous, old and intermediate-age stellar populations show considerable metallicity spreads. In part this may be due to the large age range sampled here, and the difficulty of assigning ages to individual field stars. Metallicity spreads have mainly been derived based on the color width of the red giant branch in color-magnitude diagrams, or via metallicity-sensitive photometric systems (e.g., Cole, Smecker-Hane, & Gallagher 2000; Davidge 2003). These methods have the drawback that they are affected by the age-metallicity degeneracy. Near-infrared Ca II triplet spectroscopy is now increasingly being employed for general [Fe/H] derivations instead. In the LMC, red giants in different parts of the galaxy show significantly different mean abundances (Cole et al. 2000, 2004). Cole et al. conclude that in the LMC azimuthal metallicity variations may in part be due to different fractions of bar and disk stars sampled at different positions (with the bar stars being younger and more metal-rich). With regard to field populations, star clusters have the advantage of consisting of well-datable, single-age populations. Old globular clusters in the LMC may differ substantially in metallicity (Olszewski et al. 1991). Interestingly, there is also evidence for a radial abundance gradient in the LMC old cluster population, i.e., a trend for old clusters to be more metal-rich closer to the LMC's center (Da Costa 1999). In the SMC, there are indications that intermediate-age star clusters of a given age may occasionally differ by a few tenths of dex in [Fe/H] (Da Costa & Hatzidimitriou 1998; Da Costa 2002), which would indicate considerable chemical dif-

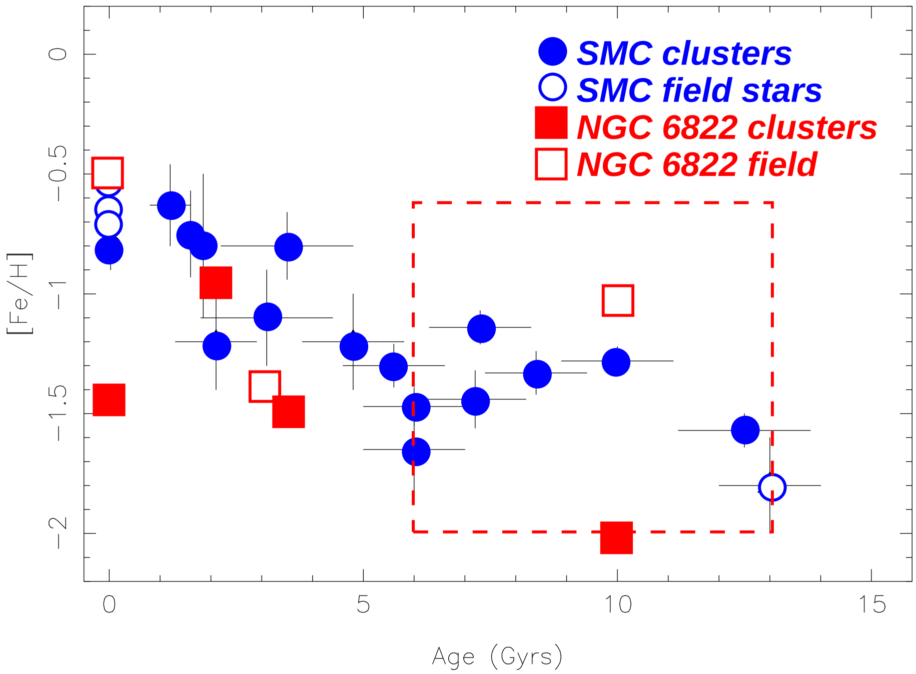

Fig. 1.3. Age versus metallicity for clusters and field stars in the SMC (circles) and in NGC 6822 (squares). The diagram for the SMC was adopted from Da Costa (2002) and comprises both spectroscopic and photometric abundances. The data points for NGC 6822 are based on a variety of different measurements and methods (clusters: Cohen & Blakeslee 1998; Chandar, Bianchi, & Ford 2000; Strader, Brodie, & Huchra 2003; field: Muschielok et al. 1999; Tolstoy et al. 2001; Venn et al. 2001) and should not be used to derive a quantitative age-metallicity relation. The solid-line box denoting the mean metallicity of NGC 6822's red giant field population is shown for an assumed age of 10 Gyr, while the much larger dashed box indicates the spread in metallicity and gives a rough idea of the possible age range.

ferences in the enrichment of their birth clouds—possibly due to infall. However, refined age determinations and more spectroscopic abundance determinations are needed to verify the SMC intermediate-age metallicity spread.

In NGC 6822 and IC 1613, abundance spreads among the field red giants have been confirmed spectroscopically (Tolstoy et al. 2001; Zucker & Wyder 2004); again, age uncertainties remain. Although the present-day field star metallicity in NGC 6822 lies between those of the LMC and the SMC, the cluster metallicities tend to lie below those of the SMC (Chandar, Bianchi, & Ford 2000; Strader et al. 2003; see Fig. 1.3). One needs to caution that the cluster measurements are based on a number of different studies and methods. Also, the present-day metallicity of NGC 6822 may have been enhanced by the recent interaction-triggered star formation episode (see §1.3.2).

1.5.3 Individual Element Abundances and Ratios

The [α/Fe] ratio in the Magellanic Clouds, NGC 6822, and WLM measured in the above studies is lower than the solar ratio. There are several possible reasons. This may be a consequence of the lower star formation rates in dIrrs or the possibility of a steeper initial mass function (see Tsujimoto et al. 1995; Pagel & Tautvaišienė 1998), i.e., a reduced contribution of Type II supernovae as compared to Type Ia supernovae (e.g., Hill et al. 2000; Smith et al. 2002), or the possibility of metal loss through selective winds (Pilyugin 1996). It seems that in the LMC, where α element abundances (most notably oxygen) were measured in clusters of different ages, the evolution of the [α/Fe] ratio was fairly flat with time (Hill et al. 2000 and Hill 2004). Field red giants also show reduced [O/Fe] values (Smith et al. 2002).

The *r*-process (traced by, e.g., Eu), which is the dominant process in massive stars, appears to prevail at low metallicities or the early stages of the LMC's evolution. The *s*-process (traced by, e.g., Ba and La), which takes place in cool intermediate-mass giants such as asymptotic giant branch stars, dominates at higher metallicities (Hill 2003). Nitrogen appears to be close to primary and may come mainly from nonmassive stars (see also Maeder, Grebel, & Mermilliod 1999). Stellar and gaseous nitrogen abundances in the Magellanic Clouds show considerable variations. Nitrogen enhancement in supergiants and old red giants may be due to mixing of CN-enhanced material to their surface during the first dredge-up (e.g., Russell & Dopita 1992; Venn 1999; Dufton et al. 2000; Smith et al. 2002; not observed, however, in LMC B main sequence stars; Korn et al. 2002).

1.5.4 Age-metallicity Relations

In order to derive a reliable, detailed, age-metallicity relation suitable to constrain the quantitative nature of the chemical evolution history of a galaxy, including the importance of infall, gas and metal loss, burstiness, etc., one would ideally want very well-resolved temporal sampling. This is not yet possible with the currently available, sparse data.

Present-day abundances are traced well by H II regions and massive stars. Progress is being made at intermediate and old ages using planetary nebulae and field red giants. Planetary nebulae have recently been used for an independent derivation of the age-metallicity evolution of the LMC at intermediate ages (Dopita et al. 1997). While extragalactic planetary nebulae cannot normally easily be age-dated, Dopita et al. extended their spectroscopic data set for the LMC to the ultraviolet to try to directly measure the flux from the central star and also used the size information for the nebulae. They were then able to not only derive abundances but also ages using full photoionization modeling, and found their results in good agreement with stellar absorption-line spectroscopy. In less massive dIrrs, the number of planetary nebulae tends to be small, making it more difficult to derive a well-sampled age-metallicity relation. In order to derive ages for individual field stars, one has to complement the spectroscopic abundances by photometric luminosities and colors and rely on isochrone models. Considerably more accurate information can presently be obtained when using star clusters as single-age, single-metallicity populations. Disadvantages of relying on star clusters are that one often only has very few such objects in a galaxy, and that their properties are not necessarily representative of the field populations.

In all Irrs and dIrrs studied in some detail to date, there is evidence for the expected increase in chemical enrichment with younger ages. The LMC's cluster age-metallicity relation clearly demonstrates this, although there is the famous cluster age gap in the age range

from ~ 4 to ~ 9 Gyr (Da Costa 2002, and references therein). The SMC has the unique advantage among all Local Group dIrrs to have formed and preserved clusters throughout its lifetime. While spectroscopic abundance determinations and improved age determinations are still missing for many clusters, the SMC shows a very well-defined age-metallicity relation with what appears to be considerable metallicity scatter at a certain given age (see Fig. 1.3, adopted from Da Costa 2002, and discussion in the previous subsection). While the age-metallicity relation appears to be flatter than predicted by closed-box models in LMC and SMC, Da Costa (2002) notes that the presently available data do not yet permit one to distinguish between simple closed-box or leaky-box evolution models, bursty star formation histories, or infall.

Figure 1.3 also shows data points for clusters and field stars in NGC 6822, for which rough age estimates and spectroscopic abundance determinations are available from a variety of different sources. As noted by Chandar et al. (2000), the clusters generally seem to be more metal-poor than the SMC clusters and NGC 6822's field population. It is unclear whether these differences would be reduced if all metallicities were determined using the same method, but overall the graph seems to indicate a trend of increasing metallicity with decreasing age. Undoubtedly, these kinds of studies will be refined in the coming years.

1.6 Other Global Correlations

1.6.1 Gas and Environment

When plotting galaxy H I masses versus distance from the closest massive galaxy in the Local Group and its immediate surroundings, we see a tendency for H I masses to increase with galactocentric distance (Fig. 1.4; Grebel et al. 2003, and references therein). Only fairly large galaxies, such as the Magellanic Clouds, IC 10, and M33, with H I masses $\gg 10^7\ M_\odot$, seem to be able to retain their gas reservoirs when closer than ~ 250 kpc to giants (Grebel et al. 2003). Note that weak lensing measurements and dynamical modeling indicate typical dark matter halo scales for massive galaxies of $260\,h^{-1}$ kpc (e.g., McKay et al. 2002). The bulk of the Local Group dIrrs and transition-type galaxies are located beyond $\sim$250 kpc from M31 and the Milky Way. At these distances these gas-rich galaxies seem to be less prone to galaxy harassment (i.e., in this case loss of gas through interactions with spirals), although the details will depend on their (yet unknown) orbital parameters (Grebel et al. 2003). A similar trend for dIrrs and dIrr/dSphs is seen in the Sculptor group (Skillman, Côté, & Miller 2003a).

Skillman, Côté, & Miller (2003b) investigated correlations between H I mass fraction and metallicity (oxygen abundance) for Local Group dIrrs and dIrrs in the Sculptor group of galaxies. They found that the Local Group dIrrs deviate from model curves expected for closed-box evolution, whereas the Sculptor group dIrrs follow these curves rather closely. Indeed the dIrrs that exhibit the strongest deviations are those with very low metallicity and gas content. Considering that the Sculptor group is, in contrast to the Local Group, a very loose and diffuse group or cloud (Karachentsev et al. 2003b), this may indicate that closed-box evolution is more likely to occur in low-density environments with little harassment.

1.6.2 Luminosity and Metallicity

Mean galaxy metallicity and mean galaxy luminosity are well correlated, as has been known for a long time. For dIrrs, one usually considers present-day oxygen abun-

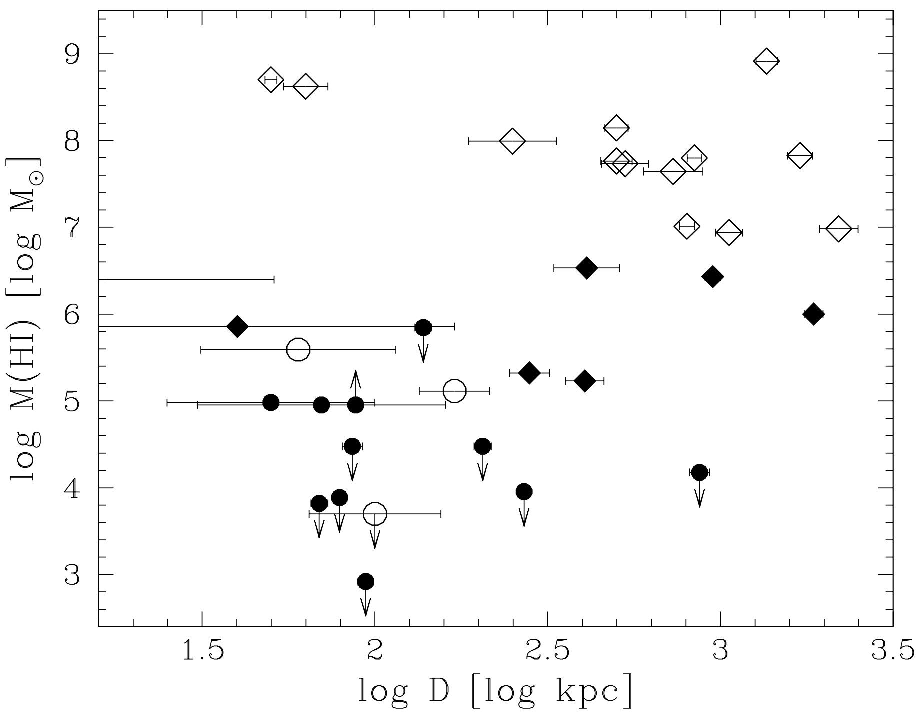

Fig. 1.4. Dwarf galaxy H I mass versus distance to the nearest massive galaxy. Filled circles stand for dwarf spheroidals (dSphs), open circles for dwarf ellipticals, open diamonds for dwarf irregulars (dIrrs), and filled diamonds for dIrr/dSph transition-type galaxies. Lower or upper H I mass limits are indicated by arrows. There is a general trend for the H I masses to increase with increasing distance from massive galaxies. DSphs lie typically below 10^5 $M_\odot$ in H I mass limits, while potential transition-type galaxies have H I masses of $\sim 10^5$ to 10^7 $M_\odot$. DIrr galaxies usually exceed 10^7 $M_\odot$. (Figure from Grebel et al. 2003.)

dances, and when comparing them to other galaxy types without ionized gas (such as dSphs), stellar [Fe/H] values are converted into what is assumed to be the corresponding nebular abundance. This conversion comes with a number of uncertainties. Grebel et al. (2003) therefore used the stellar (red giant) metallicities of Local Group dwarf galaxies of all types to directly compare the properties of their old populations. A plot of V-band luminosity L_V versus $\langle$[Fe/H]$\rangle$ (Fig. 1.5, left panel) shows a clear trend of increasing luminosity with increasing mean red giant branch metallicity. However, different galaxy types (gas-rich dIrrs and gas-deficient dSphs) are offset from each other in that the dIrrs are more luminous at the same metallicity.

In other words, the dIrrs have too low a metallicity for their luminosity as compared to dSphs. *Thus, dSphs, most of which have been quiescent over at least the past few Gyr, must have experienced chemical enrichment faster and more efficiently than dIrrs, which continue to form stars until the present day* (Grebel et al. 2003). It is tempting to speculate

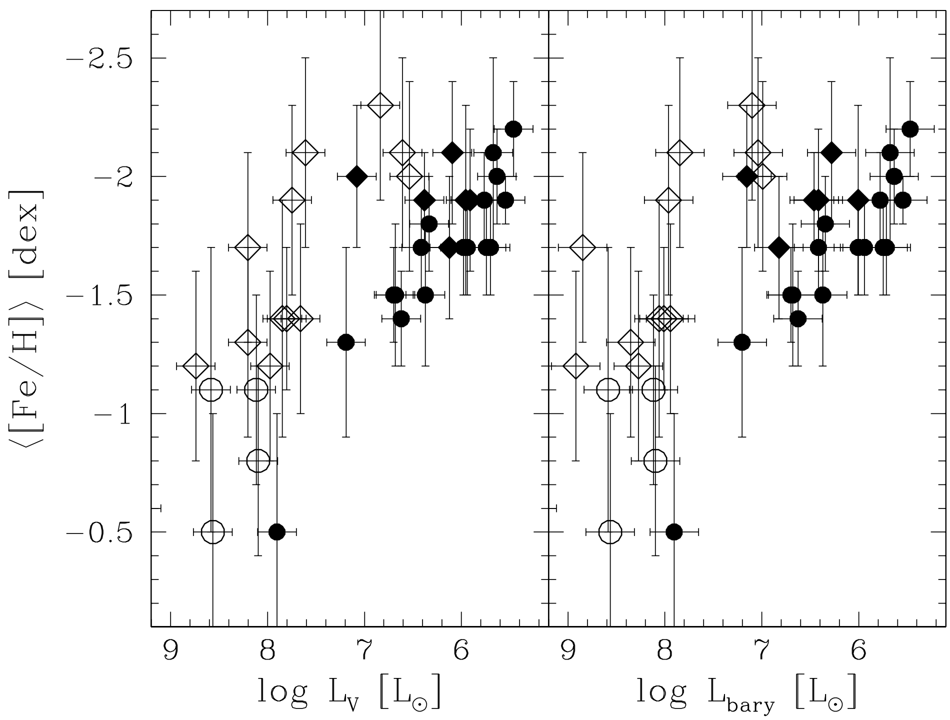

Fig. 1.5. *V*-band luminosity (*left panel*) and baryonic luminosity (*right panel*, corrected for baryon contribution of gas not yet turned into stars) versus mean metallicity of red giants. The symbols are the same as in Fig. 1.4. The error bars in metallicity indicate the metallicity spread in the old populations, not the uncertainty of the metallicity. DIrrs are more luminous at equal metallicity than dSphs. Or, in other words, dSphs are too metal rich for their low luminosity. However, several dIrr/dSph transition-type galaxies coincide with the dSph locus. These objects are indistinguishable from dSphs in all their properties except for gas content. (Figure from Grebel et al. 2003.)

that environment may once again have affected this in the sense of a denser environment leading to more vigorous early star formation rates.

When plotting the baryonic luminosity (Milgrom & Braun 1988; Matthews, van Driel, & Gallagher 1998) against metallicity (Fig. 1.5, right panel), the locus of the dSphs remains unchanged while the dIrrs move to higher luminosities as compared to the dSphs. Thus, if star formation in present-day dIrrs were terminated when all of their gas was converted into stars, then these fading dIrrs would be even further from the dSph luminosity-metallicity relation. For a discussion of the amount of fading, time scales, angular momentum loss, etc. required for converting a dIrr into a dSph, see Grebel et al. (2003). Here we simply want to emphasize that dIrrs follow a metallicity-luminosity relation that requires a different evolutionary path than in other types of dwarf galaxies. In particular, it seems that dIrrs are an intrinsically different type of galaxy than dSphs. We note in passing that for dIrrs not only do metallicities correlate well with luminosities, but also with surface brightness.

1.7 Summary

Irr and dIrr galaxies are usually gas-rich galaxies with ongoing or recent star formation. They are preferentially found in the outer regions of groups and clusters as well as in the field. Irrs and massive dIrrs exhibit solid body rotation, while low-mass dIrrs seem to be dominated by random motions. Spiral density waves are absent.

Irrs and dIrrs are often embedded in extended H I halos, which, in the absence of interactions, appear fairly regular. In low-mass dIrrs, the centroid of the H I distribution does not necessarily coincide with the optical center of the galaxy, and occasionally annular structures are seen. The neutral gas tends to be flocculent, dominated by shells and bubbles, and driven by the turbulent energy input from massive stars and supernovae. Molecular gas and dust form less easily and are more easily dissociated due to the high UV radiation field and fewer coolants in low-metallicity environments.

Irrs and dIrrs usually contain multiple distinct zones of concurrent star formation. Extended regions of active star formation tend to be long-lived and gradually migrate on time scales on a few tens to hundreds of Myr. Stochastic self-propagating star formation seems to be the main driver of star formation activity. There is no need for external triggering. In quiescently evolving dIrrs and/or dIrrs with slow or no rotation (usually the less massive dIrrs), the degree of central concentration of star formation is small, while the reverse trend is true for more massive and faster rotators. The formation of populous clusters seems to be preferred in more massive and/or interacting dIrrs. Generally, gas consumption is sufficiently low that star formation in Irrs and dIrrs may continue for another Hubble time. On global scales the star formation rate of Irrs and dIrrs is close to constant, with amplitude variations of factors of 2–3.

Old stellar populations are ubiquitous in all Irrs and dIrrs studied in detail so far, although their fractions vary widely. In contrast to the many scattered young OB associations and superassociations, older populations show a smooth and regular distribution that is much more extended than that of the young populations. Both young stellar populations and H II regions agree very well in their abundances, underlining the chemical homogeneity of Irrs and dIrrs. However, taken at face value, intermediate-age and old populations tend to exhibit considerably more scatter in their metallicity. There are indications that star clusters of the same age may differ by several tenths of dex in metallicity, although observational biases cannot yet be fully ruled out. Overall, Irrs and dIrrs follow the expected trend of increasing metal enrichment toward younger ages; the currently available data do not yet permit one to unambiguously distinguish between infall and leaky-box versus closed-box chemical evolution, nor to reliably evaluate the importance and impact of possible bursts.

Substantial progress is being made not only in spectroscopic measurements of stellar metallicities, but also in the determination of individual element abundances. The [α/Fe] ratios in Irrs and dIrrs, which tend to be lower than the solar ratio, and the lower effective yields may be interpreted as indicative of lower astration rates and a reduced contribution of Type II supernovae. Other interpretations (different initial mass functions, leaky-box chemical evolution with metal loss through selective winds) are being entertained as well.

Correlations between gas content and distance from massive galaxies as well as morphological segregation indicate that environment (in particular gas loss through ram pressure or tidal stripping; see also Parodi, Barazza, & Binggeli 2002; Lee, McCall, & Richer 2003 for the Virgo cluster) does have an impact on the evolution of Irrs and dIrrs. Irrs and dIrrs follow the well-known relation of increasing mean metallicity with increasing galaxy luminosity.

The offset in this relation from the relation for dSphs, such that dIrrs are more luminous than dSphs at the same metallicity, indicates that the early chemical evolution in these two galaxy types proceeded differently, with dSphs becoming enriched more quickly.

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